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A first-principles causation hypothesis for pillar bursts in underground coal mines

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A FIRST-PRINCIPLES CAUSATION HYPOTHESIS FOR PILLAR BURSTS IN UNDERGROUND COAL MINES

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ABSTRACT: A review of published literature reveals case histories whereby the entire periphery of a coal pillar has "*burst*" out as a single event during first workings, the associated energy and material release causing significant damage to adjacent roadways and any equipment/infrastructure located within said roadways. Such events are distinct from coal burst events during first workings such as that at the Austar Mine in 2014, or those linked to overburden bumps related to either horizontal stress-driven slip along major faults and/or thick, massive strata units in the overburden or floor of the coal seam. The paper considers as to how the necessary "*unstable*" conditions for a pillar burst event could conceivably be generated, based on established coal pillar mechanics, specific pillar loading conditions and the shear-restraint of horizontal planes according to both cohesion and friction. The associated hypothesis is applied to a published example to test its veracity.

The longer-term objective of this type of back-analysis is to provide a "*cause and effect*" list of geological, geotechnical and mine layout circumstances that can and indeed have resulted in entire coal pillar bursts during underground coal mining activities, being able to predict the likely propensity for such events prior to mining being a mandatory requirement in an effective prevention or consequence mitigation process.

INTRODUCTION

The rapid expulsion of coal material into mine workings is both a potentially destructive, in terms of mine safety and production, and relatively poorly understood phenomenon in underground coal mining. Coal industries from around the world, particularly those with deep mines, report such events on an infrequent basis, with the principles of fundamental cause and effect remaining elusive. As recently as 2017, Dr Chris Mark published a paper with the provocative title "*Coal Bursts that Occur During Development: A Rock Mechanics Enigma*" (Mark 2017) which clearly confirms the basis of the preceding opening statement. Within Mark 2017 a series of what are described as "*pillar bursts*" case histories are discussed whereby the entire periphery of one or more coal pillars has reportedly undergone bursting as a single event relatively soon after roadway development. Figure 1 from the Manalapan No.17 Mine in Kentucky indicates two such reported pillar bursts, as described by Newman (2002):

> *The bump impacted six pillars with the greatest damage centered in the belt entry, two breaks outby the active face. Roughly 3–4 m of the pillars on either side of the belt entry ailed. The belt entry two breaks outby the face was filled with fine coal in the center of the entry…The coal in the remaining portion of the pillar was separated from the roof creating a void space, approximately 3 m deep into the pillar.*
>
> *The height of the void space was roughly 0.3–0.5 m at the edge of the remaining portion of the pillar, grading back to contact with the roof…..Although no roof falls were visible, wide spans in excess of 12 m resulted from the void space that formed between the top of the bumped pillars and the immediate roof.*

It was stated that no unusual geological features were noted in the vicinity of the burst sites, Figure 2 showing roadway conditions following the pillar burst. Mark (2017) commented that the underlying workings are first workings with limited areas of extraction, and that the burst pillars in the overlying Kellioka Seam have back-analysed ARMPS Stability Factors (SF) in the order of 2, which would normally suggest a stable pillar system. Demonstrably then, another failure mechanism must be at work that has no direct link to traditional coal pillar design.

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What is immediately obvious in Figure 1 is that the areas of burst pillars in the Kellioka Seam align almost exactly with remnant pillars in the underlying Harlan Seam workings. Furthermore, the burst pillars coincide with the cover depth being more than 457 m (1500'). The reported response of the mine was to impose mining restrictions above certain cover depths, the final upper limit being 300 m.

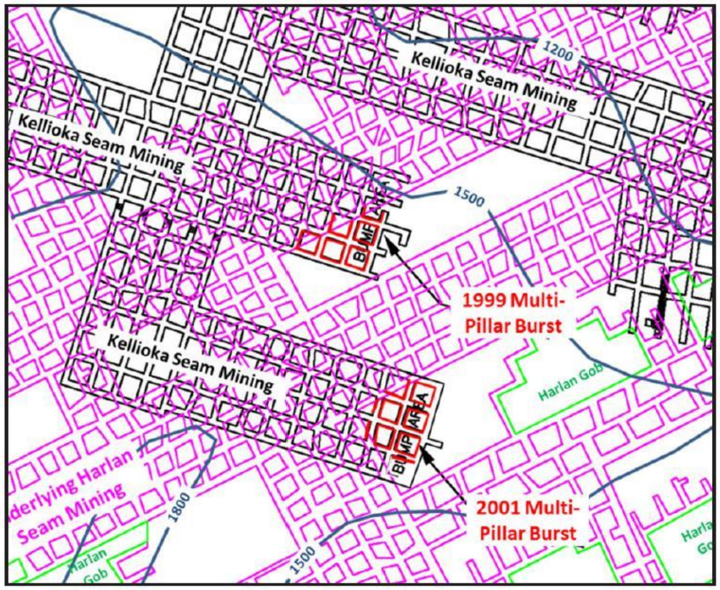


Figure 1: Locations of Burst Events in the Manalapan No. 17 Mine (Black) relative to underlying Harlan seam workings (magenta and green) – Mark 2017

Figure 2: Conditions in an entry at the Manalapan No. 17 Mine after the 2001 Burst (Mark 2017)

The reported pillar burst experience from the Kellioka Seam at the Manalapan No.17 Mine strongly suggests that the primary driver is excessive vertical stresses within what should otherwise be stable coal pillars. This leads to the inevitable question as to how stable coal pillars that are subjected to relatively low multi-seam vertical stress impacts by virtue of the nature of the underlying workings, can seemingly "*explode*" without significant warning? This is the main subject of this paper, the intention being to develop an initial hypothesis that might then be tested by others by reference to other case histories over time.

RELEVANT PRECEDENT

Frith, *et al. (*2019) described a first principles cause and effect model for the 2014 development coal burst at the Austar Mine in NSW, which in hindsight had several similar geological characteristics to documented development bursts at the Sunnyside Mine in Utah. That model was directly linked to two geological features, namely very specific geological faulting just inbye the Austar burst site, and the presence of a planar, low friction horizontal plane within the coal seam, known as the Dosco Band, which marked the top of the burst coal section (see Figure 3).

Figure 3: Incident scene showing the left-hand side of continuous miner (NSW Department of Industry, 2015)

Without digressing into the technical detail, the three major drivers for the Austar development coal burst were assessed to be:

i. A localised increase in the major horizontal stress within the coal seam.

ii. A localised reduction to effectively zero of the minor horizontal stress within the coal seam.

iii. The presence of a low friction plane towards the top of the working section.

The effect of (i) and (ii) was taken to cause a significant and highly unusual imbalance in the horizontal stresses within the coal seam, such that the major horizontal stress was "unstable" due to a lack of confinement in the orthogonal or minor direction. The effect of (iii) was to eliminate the stabilising influence of the vertical stress, the inevitable result being a very rapid unloading of the major horizontal stress within the coal seam below the low friction plane and a resultant very high acceleration of the effected coal, which caused coal to be ejected rapidly into the mine roadway in the form of a "burst".

The Austar incident and those reported from the Sunnyside Mine can be directly linked to a major geological faulting system, this being taken to be the local anomaly that brought about the specific ground stresses within the coal seam that theoretically allow coal bursts to occur if a suitable low friction plane also exists within the coal seam. In the case of the Manalapan No.17 Mine, no such major structures exist; hence the question posed is whether similarly unstable ground stresses can develop within the coal seam without the influence of a major geological structure?

PRESENCE OF A LOW FRICTION PLANE

Figure 2 demonstrates that the coal seam to stone roof contact in the area of pillar bursts at the Manalapan No.17 Mine is characterised by what appears to be a planar and smooth surface. Hence, the first requirement for a coal burst is present, the remainder of the paper focusing on horizontal stresses within the coal seam and how they might become critically unstable in this particular case.

HORIZONTAL STRESSES WITHIN COAL

A general model for the development of *in situ* horizontal stresses within coal measures was put forward by Nemcik, *et al.,* (2005) as follows:

$$\sigma_H = \sigma_v.(v/1\text{-}v) + E.TSF_H \qquad [1]$$

$\sigma_h = \sigma_v.(v/1\text{-}v) + E.TSF_h$ [2]

$\sigma_v = p.g.h$ [3]

where:

σ_H = major horizontal stress
σ_h = minor horizontal stress
v = Poisson's Ratio
E = Young's Modulus
TSF = Tectonic Stress Factor (H = major and h = minor)
σ_v = vertical stress as given by weight of overburden considerations
(v/1-v) = numerical determination of K_o.

Cartwright (1997) examined the relationship between horizontal stress and depth using the same model as that which was later published by Nemcik, *et al.,* (2005) according to his database of UK coal mining stress measurements. His statistical analysis applied the following equation, which is identical to [1] in its form other than the inclusion of an arbitrary constant:

$S_H = B_0 + B_1 [(v/(1+v)) (\text{Depth})] + B_2 (\text{Modulus})$ [4]

B_0 is a constant with units of MPa, B_1 is a constant with units MPa/m, v is Poisson's Ratio, and B_2 is the "Tectonic Stress Factor" or TSF.

Regression analyses returned the following values for the constants, with an R-squared of 0.94:

B_0 = -4.0 MPa

B_1 = 0.009 MPa/m, and

$B_2 = 0.78*10^{-3}$

Whilst Cartwright's analysis indicated that Yong's Modulus was more important than the depth for predicting the maximum horizontal stress, this would logically be expected from a stress measurement data set that is almost certainly taken from within pre-dominantly high modulus stone materials. What is intriguing in the context of this paper, which is considering horizontal stresses within low modulus coal, is that the B_1 value of 0.009 MPa/m is generally consistent with a vertical stress gradient of 0.025 MPa/m, in combination with a K_o value in the order of 0.33 (which is linked to a Poisson's Ratio of 0.25).

From the Cartwright (2007) analyses, it is inevitably concluded that K_o related *in situ* horizontal stresses are almost certainly "*alive and well*" in coal measures strata, this then potentially including coal.

THE LINK BETWEEN POISSON'S RATIO AND K_O HORIZONTAL STRESS

Poisson's Ratio is the ratio between transverse and axial strains when a material is loaded axially, as shown in Figure 4. It is taken to be an elastic property with values ranging between 0 and 0.5.

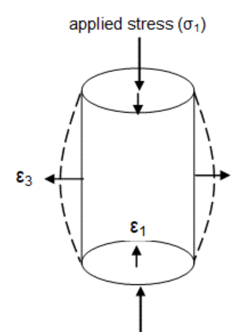


Figure 4: Schematic Illustration of Poisson's Ratio

In terms of how Poisson's Ratio is linked to K_o horizontal stresses, Figure 5 shows a number of rock testing specimens that are hypothetically confined at their extremities and are all being compressed vertically, the resultant horizontal interaction between the samples as they all laterally expand being the source of the induced K_o horizontal stress.

With a typical value of Poisson's Ratio for coal being in the order of 0.25, K_o as given by [3], becomes 0.33, such that for every 3 MPa of vertical stress, the associated K_o horizontal stress is in the order of 1 MPa.

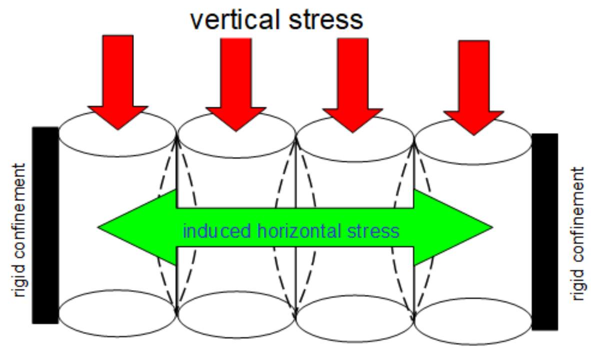


Figure 5: Schematic Illustration of K_o Horizontal Stress generation

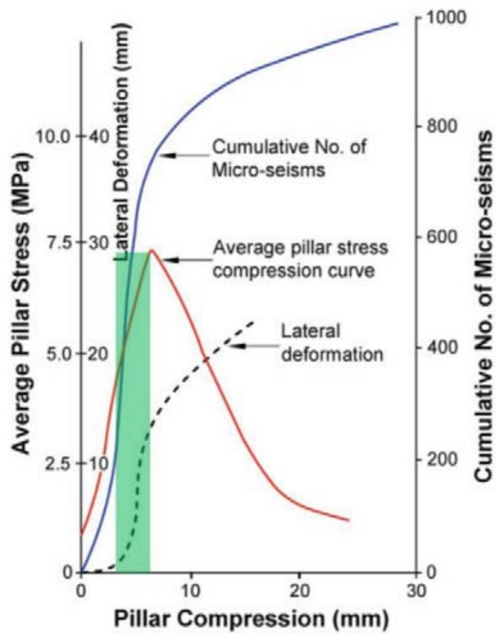


Figure 6: Behaviour of *In Situ* test pillars during compression (Wagner 1974 as illustrated by Galvin 2016)

ELASTIC LIMIT OF POISSON'S RATIO

As with all elastic material properties, Poisson's Ratio is inevitably limited by the elastic axial strain limit in line with Hooke's Law. The question in the context of this study is what happens to transverse or lateral strain relative to axial strain between the limits of an elastic Poisson's Ratio with a value in the order of 0.25 and the ultimate failure or maximum load-bearing ability of coal?

Fortunately, *in situ* testing results from the vertical compression of coal pillars in South Africa in the 1970's provide invaluable insights into this issue, as illustrated in Figure 6.

The green shaded area of Figure 6 identifies a specific portion of the axial load-displacement (stress-strain) curve that is within the second half (3 mm to 6 mm pillar compression) of that curve leading up to the maximum coal or pillar strength. The critical characteristic of this area is that the measured lateral deformation increases rapidly as compared to within the first half of the curve, whereby the axial stress is no more than 50% of the ultimate strength and lateral deformation is in the order of 1 mm. Critically, from 3 mm to 6 mm of pillar compression, the measured lateral deformation increases from 1 mm to 12 mm, with the final condition just before coal failure being that of a vertical pillar compression of around 6 mm and a lateral deformation in the order of 12 mm. This is inconsistent with a Poisson's Ratio of 0.25.

Based on the Wagner (1974) data, once coal or a coal pillar is compressed into the second half of its stress-strain curve, there appears to be a significant increase in the rate of lateral expansion of the coal, to the point that an elastic Poisson's Ratio in the order of 0.25 becomes meaningless. This is worthy of further consideration in the context of the development of horizontal stresses within coal pillars under the action of high vertical stresses, both pre-mining and induced by mining.

PRE-MINING VERTICAL STRAINS IN COAL SEAMS

Prior to mining, the vertical strain in a coal seam is inevitably dictated by the weight of overburden that is acting on it. This is a simple and irrefutable concept.

Frith and Reed (2018), when discussing whether it is the coal pillars or the overburden that fails first prior to major pillar collapse, indicated that for pillar w/h ratios of 1 to 5, vertical strains at pillar failure were in the order of 1% according to laboratory-based coal testing data, as reported by Das (1986) for example as shown in Figure 7.

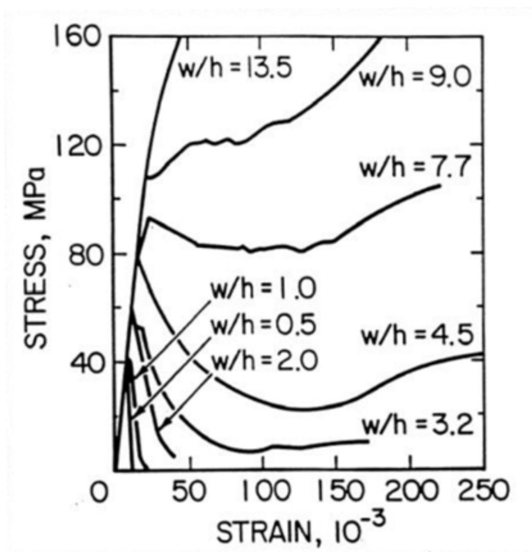


Figure 7: Stress-Strain behaviour of coal for varying width to height (*w/h*) ratio (Das, 1986)

Based on the green-shaded area in Figure 6, the onset of increasing lateral deformation commences at an axial strain in the order of 50% of that at ultimate coal strength, which is therefore estimated to be in in the order of 0.5% (i.e. 50% of 1%).

Assuming an *in situ* Young's Modulus for coal in the order of 2 GPa, 0.5% axial strain equates to an applied vertical stress in the order of 10 MPa, which is broadly equivalent to a cover depth of 400 m (i.e. 0.025 MPa/m x 400 m).

In other words, once the pre-mining vertical stress in coal exceeds around 10 MPa due to either a cover depth of 400 m or a lesser cover depth in combination with multi-seam vertical stress intensification, the upper limit of an elastic Poisson's Ratio for coal is potentially reached. Specifically, due to the significantly increasing lateral expansion of coal above this limit, it would logically be expected that the induced horizontal stresses within the coal will become substantially higher than given by an equivalent elastic K_o analysis.

This provides a potential explanation for the source of substantially increasing major horizontal stresses within low Young's Modulus coal seams at depths more than 400 m or in association with multi-seam vertical stress interactions at depths > in the order of 300 m.

SHEAR SLIP CONDITIONS ON HORIZONTAL PLANES OF WEAKNESS

Figure 8 contains a simple representation of the major horizontal stress in coal and the vertical stress along a horizontal pre-existing plane of weakness, the confining influence of the minor horizontal stress being ignored for the moment.

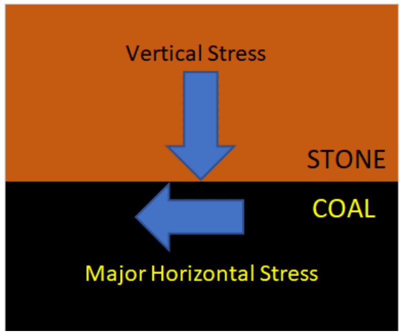
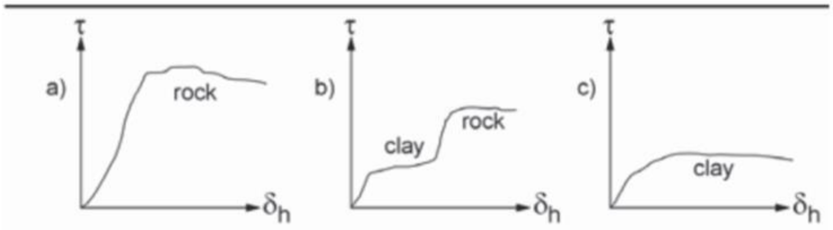


Figure 8: Vertical and horizontal stress conditions at coal to stone interface

If the major horizontal stress is in the order of one-third the vertical stress, then ignoring any cohesive strength of the plane of weakness, a friction angle of only 18° ($\tan^{-1}0.33$) is required to prevent shear slip along the plane under the action of the major horizontal stress. Referring to Figure 9, it is clear that this is only likely achieved in association with either the presence of fine infilling material on the surface or a sheared surface, as intact, clean surfaces all have estimated friction angles > 34° irrespective of the surface condition.



(a) Rock wall contact		(thin coatings)				
	J_a/J_r =	0.75	1.0	2	3	4
		$\tan^{-1}(J_r/J_a)°$				
A. Discontinuous joints	4	79°	76°	63°	53°	45°
B. Rough, undulating	3	76°	72°	56°	45°	37°
C. Smooth, undulating	2	69°	63°	45°	34°	27°
D. Slickensided, undulating	1.5	63°	56°	37°	27°	21°
E. Rough, planar	1.5	63°	56°	37°	27°	21°
F. Smooth, planar	1.0	53°	45°	27°	18°	14°
G. Slickensided, planar	0.5	34°	27°	14°	9.5°	7.1°

(b) Rock wall contact when sheared		(thin fillings)			
	J_a/J_r =	4	6	8	12
		$\tan^{-1}(J_r/J_a)°$			
A. Discontinuous joints	4	45°	34°	27°	18°
B. Rough, undulating	3	37°	27°	21°	14°
C. Smooth, undulating	2	27°	18°	14°	9.5°
D. Slickensided, undulating	1.5	21°	14°	11°	7.1°
E. Rough, planar	1.5	21°	14°	11°	7.1°
F. Smooth, planar	1.0	14°	9.5°	7.1°	4.7°
G. Slickensided, planar	0.5	7°	4.7°	3.6°	2.4°

Figure 9: Friction angles according to varying discontinuity condition (Barton, 2007)

However, this changes substantially if it were the case that the major horizontal stress in the coal were at equal in magnitude to the vertical stress, which based on the previous analyses is judged to be a credible possibility in certain situations. The major horizontal stress and vertical stress being equal in magnitude requires a minimum friction angle of 45° to prevent shear slip along the plane. If the major horizontal stress in the coal were 1.5 times the vertical stress, the required friction angle then increases to 56°.

Based on Figure 9, it can be seen that smooth and slickensided planar surfaces (as shaded in red) would not provide sufficient frictional shear restraint to prevent the major horizontal stress overcoming the restraint of the vertical stress, this being entirely consistent with the coal to roof contact that is visibly evident at the Manalapan No.1 17 Mine pillar burst site in Figure 2.

REDUCTION IN THE MINOR HORIZONTAL STRESS

Unlike the Austar development coal burst model whereby the loss of minor horizontal stress was judged to be due to a pre-existing geological void within the coal seam linked to the development of "*wing cracks*" as a direct result of horizontal shear slip along a major geological fault, an increasing major horizontal stress within a coal seam due to K_o effects more generally, will also act to increase the orthogonal minor horizontal stress, as K_o effects do not logically result in a directional horizontal stress bias (see Figure 10).

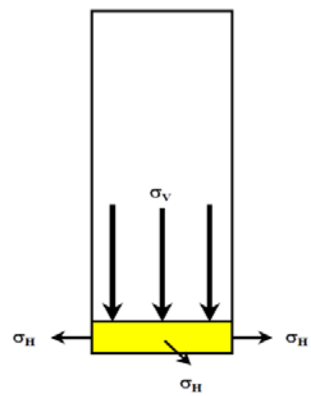


Figure 10: Schematic illustration of Poisson's effect under the action of vertical stress (Frith, 2002)

The question therefore is how the stabilising influence of the minor horizontal stress can be overcome if there is no pre-existing void within the coal seam to allow it to be relieved over geological time prior to mining. With no major geological structures at the various pillar burst sites in the Manalapan No.17 Mine, another explanation is sought.

The only credible source for horizontal stress relief is the effect of the roadways surrounding a coal pillar, as will now be considered further by reference to the various "zones" within pillars.

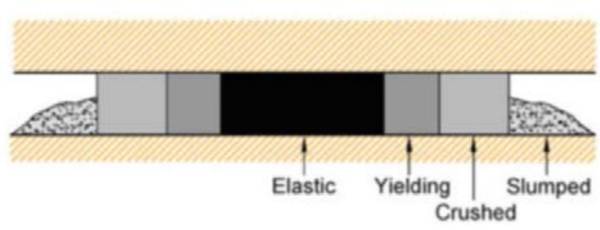


Figure 11: Zones developed within a coal pillar (Galvin, 2016)

A commonly accepted zonal model for coal pillars is shown in Figure 11. It illustrates the changes in condition of the coal due to the pillar being formed and subsequently compressed vertically, the coal becoming less stable towards the outside of the pillar, with the central "elastic" core being the main source of pillar strength. The model also implies that the coal must have been in an elastic state prior to mining, which is why the central section or core of the pillar post-mining is defined as still being elastic.

For higher width to height (w/h) ratio pillars (> 4 to 5), coal pillars are influenced by a further phenomenon in that the central core becomes "*confined*" as a result of frictional restraint at contacts preventing the coal from expanding laterally as it is vertically compressed (see Figure 12). Whilst technically the core of the pillar remains "elastic", it is only by virtue of the horizontal confinement being generated as the coal is further vertically compressed. It is this mechanism within the core of a pillar that gives rise to the ever-increasing strength of a coal pillar and the elimination of a strain-softening or collapse mode of failure as a direct function of w/h ratio (see Figure 13).

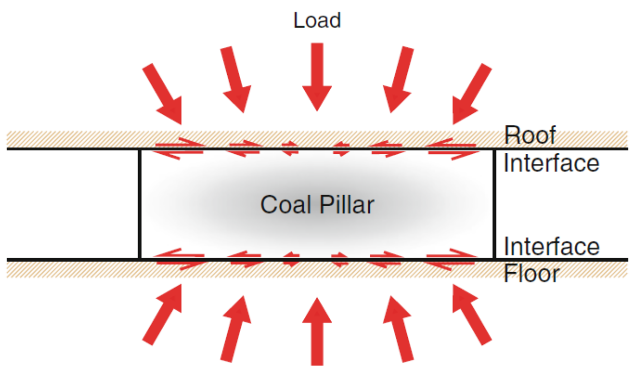


Figure 12: Diagram showing how shear resistance to lateral pillar dilation is generated on the contact surfaces of a pillar (Galvin, 2016)

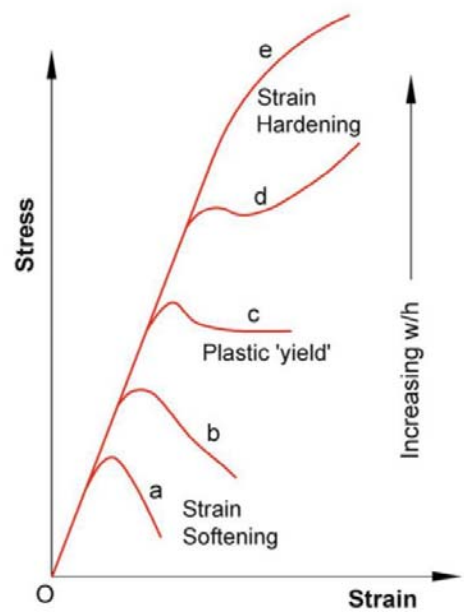


Figure 13: Effect of w/h ratio on the stress-strain pillar characteristics (Galvin, 2016)

Under the model shown in Figure 11, the confined core of a high w/h ratio coal pillar is separated from mine roadways by coal material that is in varying states of failure, logically due to a lack of horizontal confinement. In other words, the coal around the perimeter of the pillar tends to provide a physical and quite substantial barrier between the mine workings and the highly stressed central pillar core.

However, if the coal itself were already compressed beyond its elastic limit prior to mining, as previously described, then in effect the confined core of the pillar would pre-exist mining and so logically extend to the edges of the pillar immediately that a roadway is formed. This gives rise to an entirely different scenario than the model shown in Figure 11, as:

i. The coal is already in a non-elastic pre-mining state by reference to Figure 6.

ii. Elevated horizontal stresses are therefore likely acting within the coal at the edges of the pillar.

iii. The formation of the roadway removes the confinement (i.e. the coal) that allowed those elevated horizontal stresses to ever be generated prior to mining.

iv. Containment of horizontal stress in the coal at the edge of the pillar becomes entirely reliant upon the shear strength of the restraints along contact surfaces, as illustrated in Figure 12.

v. Critically, there is no immediate coal "barrier" in place to protect mine roadways from a highly stressed pillar core, which now extends to the edges of the pillar.

With the "confined core" of the pillar extending throughout the pillar to the edge of the roadways, the necessary conditions for coal to burst out into the mine workings have been established by the simple act of driving roadways, the only effective control being the cohesion and friction along horizontal contacts within the coal seam.

With the entire perimeter of a small coal pillar being in such a "burst-prone" condition, the ability of one side of a pillar to burst out between parallel roadways in a single event becomes understandable, at least conceptually. When it is also considered that the perimeter around the pillar is likely a quasi-continuous structure, the entire perimeter bursting out in response to one side becoming unstable, would also make sense.

Having established that the pre-mining condition of coal can give rise to coal burst potential at the edges of a coal pillar, it is worth considering any further influence of mining-induced vertical stress increases.

INDUCED VERTICAL AND HORIZONTAL STRESSES DUE TO PILLAR FORMATION

On the basis that roadway widths are essentially fixed, the vertical stress increase on each coal pillar due to mining increases as a direct function of reducing coal pillar size. For 24 m x 24 m roadway centres and 6 m wide roadways (as assumed for the Manalapan No.17 Mine cases), the total vertical stress acting on each coal pillar is almost double the pre-mining value.

Simply, if the coal around the perimeter of a coal pillar is not highly confined by pre-existing horizontal stress, it will inevitably tend to fracture and fail similar to that in an unconfined laboratory test under the action of increasing vertical stress due to mining, the end result being the zonal model shown in Figure 11 whereby the confined core and mine roadways are physically isolated from one another. Increasing the vertical stress on the pillar due to mining simply exacerbates the coal yielding and failure processes around the perimeter of the pillar, with the core and roadways then always remaining isolated from one another.

However, if the coal around the perimeter of a pillar is already in a suitably high triaxial state when roadways are driven and this is maintained by the action of friction along the contacts, it may then act to prevent the coal failing under increasing vertical loading as the rate of horizontal stress increase with vertical stress increase is also rising, as shown in Figure 6. Under this scenario, the increasing vertical stresses on a coal pillar due to mining may drive the perimeter of the pillar from one that is initially stable, albeit containing elevated horizontal stresses, to one whereby the ratio of horizontal stress to vertical stress in the coal has the ability to result in shear failure along a horizontal contact (Figure 8), with the coal then inevitably bursting out into the roadway due to horizontal stress unloading and coal acceleration, the mechanics of which are fully explained in Frith, *et al.,(* 2019).

If this pillar burst model has credibility, it should be the case that prior to a pillar burst, minimal rib spall ("slumped" coal in Figure 11) was observed with few obvious pre-cursor warnings signs, this having been the case with the Austar incident in 2014. In relation to the pillar bursts at Manalapan No.17 Mine, Newman 2002 makes the following statements, noting his use of the term "bump" rather than "burst":

> *"Prior to the first bump on December 6, 1999, mine personnel stated that there was no bumping or "working" of the roof or rib, no rib spalling, and no floor heave. Strain energy continued to build undetected until a bump occurred that damaged several pillars. The concern of mine personnel was that the bump had occurred without a series of precursor events. Mine management decided to abandon and seal the section and drive a parallel submain."*
>
> "*However, beginning two days before the second bump on September 22, 2001, there were numerous small bumps at the face*".

In other words, despite the pillars that eventually underwent a pillar burst, being formed at a cover depth in excess of 450 m and being impacted by some level of multi-seam vertical stress interaction, no rib spall prior to the first pillar burst was reported, only the occurrence of presumably minor "bumping" events at the face in the second example.

The lack of rib spall is explained by the inferred existence of high levels of horizontal confinement in the coal at the edges of the pillar when roadways are first driven. The minor bumping events that preceded the second burst at the Manalapan No.17 Mine, are taken to be indicative of marginally stable contact conditions under the action of horizontal confinement within the general area.

The same model of the confined core extending to the edge of the pillar due to the pre-existing state of the coal, also infers that more than one pillar burst event can occur if the burst coal in the surrounding roadways is subsequently removed, the reason being that this coal is acting to confine the perimeter of the remaining core of the pillar, in the same way that the "yielded", "crushed" and "slumped" coal do in Figure 11. The tragic second major event at Crandall Canyon is entirely consistent with this scenario.

Finally in this section, it is interesting to consider that other coal industries routinely develop roadways at far greater depths under multi-seam stress interactions than those that have proven to be pillar burst prone in the USA. The mining layouts tend to incorporate either single entry drivages or wide, long pillars, the minimum width of which is commonly designed according to a one-tenth of the depth rule. In contrast, the coal pillars that burst at the Manalapan No.17 Mine, as shown in Figure 1, whilst being reported as having ARMPS Version 6.0 SF values in excess of 2 (Mark, 2017) had solid widths of around 18 m (24 m centres and assumed 6 m wide roadways), which at a cover depth in the order of 500 m is only one-thirtieth of the cover depth. The pillars were also square rather than being distinctly rectangular.

What this inevitably leads to is the hypothesis that in the same way that low w/h (< 4 to 5) coal pillars need to be designed in section (i.e. by their width and height) to remain stable under the action of vertical stress by virtue of the pillar strength, higher w/h ratios pillars that develop an internal confined core that increases pillar strength, need to be designed in plan (i.e. by their width and length) in order to ensure that if the confined core is likely to extend to the outer edge of the pillar by virtue of the level of pre-mining coal compression, it retains its stability under the action of the horizontal stresses that are subsequently generated as a direct function of the induced vertical stresses on the pillar due to mining.

CONCLUSIONS

A review has been conducted on two reported coal pillar bursts in the US in an attempt to identify a cause and effect model that explains why such destructive events can occur on an infrequent and seemingly random basis. This was required to further develop the Venn Diagram classification of coal bursting events following an analysis of the development coal burst event at the Austar Mine in 2014 (Frith, *et al.,* 2019) and overburden bump causation mechanisms (Frith, *et al.,* 2020) – see Figure 14.

The starting point for the analysis was the cause and effect model developed by Frith, *et al.,* 2019 for the 2014 development coal burst at the Austar Mine, which is based on the coal bursting mechanism of the major horizontal stress in the coal seam becoming unstable and therefore rapidly unloading in the manner of an elastic spring. For this to occur, an elevated major horizontal stress and substantially reduced minor horizontal stress in the coal, along with a low friction plane at or towards the top of the roadway, are required for the major horizontal stress to become unstable and so unload in a violent manner. Such conditions can demonstrably come about in proximity to very specific geological faults as are known to exist at both the Austar Mine burst site and the Sunnyside Mine in Utah more generally, which also reportedly suffered with development coal bursts.

Pillar bursts where the entire perimeter of one or more coal pillars fail violently, cannot be explained by the Austar-type development burst model, however it provides a useful starting point from which to consider how and why pillar bursts may occur, the need for a low friction horizontal contact plane being common to both models.

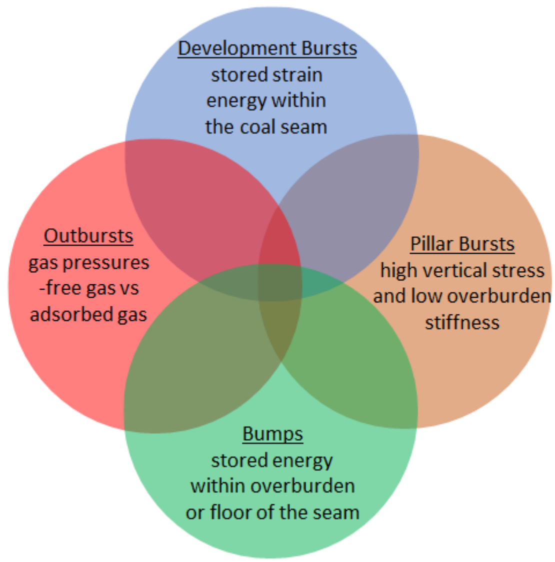


Figure 14: Suggested classification of high energy release events in underground coal mining for four fundamental event types (Frith, *et al.,* 2020)

Aged *in situ* testing data from coal pillars indicates that well before the ultimate strength of a coal pillar is reached, the rate at which the coal laterally expands under increasing vertical compression can exponentially increase so that the elastic magnitude of Poisson's Ratio no longer applies. The logical consequence of this is that if adequate restraint exists, substantially higher horizontal stresses can be generated within the coal seam under the action of vertical stress, as compared to the coal seam being within the vertical compression range where Poisson's Ratio applies. A general transition point has been estimated at a cover depth of around 400 m, which immediately explains the anecdotal significance of high cover depth and/or multi-seam vertical stress interactions on pillar burst potential.

If the pre-mining state of the coal contains elevated level of horizontal stress that are greater than those that would be generated by the elastic value of Poisson's Ratio, it is argued that the traditional model of zoning within a coal pillar (as illustrated in Figure 11), does not necessarily apply, the central elastic core of a higher w/h ratio pillar potentially extending to the outside edge of the pillar. This sets up the dual conditions of (a) reduced rib spall by virtue of higher horizontal confinement within the coal at the edge of the pillar, and (b) pillar burst potential, the prevention of which is dictated by (i) the shear strength of the various horizontal contacts, (ii) limiting the magnitude of the vertical stress increases that are developed due to mining and (iii) maintaining the integrity of the minor horizontal stress within the coal.

As the induced vertical stress on the pillar due to mining is an integral part of the pillar burst model, it logically follows that the failure of any part of the confined core in one pillar by bursting, would act to increase the vertical stresses acting on adjacent pillars. Therefore, one such failure would have the potential to induce others in adjacent pillars, particular under a softer overburden loading system due to multi-seam mining effects. This is known to have occurred.

Experience from deep mining industries more generally appears to indicate that pillar bursts can potentially be averted by the use of wider and longer pillars, as compared to the more common use of small, square pillars that are often sized for place change development purposes. Wider and longer pillars achieve two things; (i) they keep parallel roadways further apart and (ii) they reduce the magnitude of mining-induced vertical stress increases on the pillar.

It is therefore hypothesised that coal pillar design under potential pillar burst conditions around the perimeter of a pillar, needs to analyse the pillars in plan, as well as in section, to ensure that the outside perimeter of the pillar remains stable under the action of horizontal stress within the coal. A suitable design method for pillars with w/h ratios > 4 to 5 is yet to be developed, but anecdotal evidence suggests that it is pillar width and length that are the controlling parameters for pillar bursts, in the same way that pillar width and height control the strength and stability of the pillar under vertical loading at lower w/h ratio pillars.

If nothing else, this hypothesis opens up the potential for coal to be mined without the threat of pillar bursting via the use larger pillar dimensions in plan (if necessary), rather than significant coal reserves necessarily being sterilised by maintaining the use of small pillars, thereby limiting the maximum cover depth where safe mining can be achieved.

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